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Life cycle assessment of industrial scale production of *spirulina* tablets

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ABSTRACT

Spirulina platensis has been successfully commercialized as functional food ingredients, animal feed and medicine due to its high contents of protein, beta-carotene, vitamins, and minerals. In this study, we investigated the environmental performance (cradle-to-gate) of edible *Spirulina* tablets using Life Cycle Assessment (LCA). A comparative analysis with other three traditional foods or diets was conducted by using various nutrient values as functional units (e.g., protein content and a composite nutrient score) in the analysis. This research showed that *Spirulina* tablets production for protein caused environmental impacts mainly in fossil fuel use, acidification, climate change, smog formation, and eutrophication. The impact of the cultivation stage was the highest environmental impacts among all production stages resulting from the extensive use of chemicals, nutrients, and energy. The impacts of algae food production are around 2–5 times to algae production for biofuels which was also modeled in this study. In terms of protein production, algae tablet cause higher impacts than traditional terrestrial crops but lower impacts than protein from animal products. However, as the algae contain a wide variety of nutrients, especially high micronutrients such as the beta-carotene, the environmental impacts of producing the same nutrient combinations of protein and beta-carotene from carrot + tofu were higher than producing *Spirulina* tablets. The results in this work can be used to assess edible algae production inventories and provide reliable information for development of more sustainable products and processes.

1. Introduction

Microalgae are excellent natural sources of highly valuable bioactive compounds, and have become the most promising and innovative sources of new food and functional products in the 21st century [1]. *Spirulina platensis*, a special microalgae species, is rich in protein, beta-carotene, vitamins, and minerals, which makes it the most ideal natural nutrition supplement that meets requirements set by Food and Agriculture Organization (FAO). It was granted Generally Recognized as Safe (GRAS) status by Food and Drug Administration (FDA) in 2003 [2,3]. Researchers have demonstrated that *Spirulina* can improve the immunity of organism, promote calcium absorption and prevent aging [1,4]. It has been commercialized successfully as a dietary supplement with the forms of tablet, flake and powder, and also as a feed supplement in the aquaculture, aquarium and poultry industries [5,6].

Spirulina platensis was introduced to China in the 1980s as a national strategic program in the 7th Five-Year Plan for the country [7]. By the mid-1990s, China had become the largest *Spirulina* producer in the world. In the last decade, the microalgae industry in China had been developing rapidly and has made remarkable achievements. According to the International Energy Agency (IEA), the total world production of dry algal biomass is estimated at about 10,000 tons per year with half of the yield being produced in mainland China [8]. Currently, there are more than 60 cultivation plants in China, producing around 9600 tons of algae powder, which accounts for 80% of the world's total output and generates \$570 million annually [9]. With increasing environmental and health awareness in China over the last decades, researchers, industries and consumers have become more interested in the environmental benefits and nutritional value of the *Spirulina* cultivation and derived products. It is recognized that environmental impact analysis is crucial to the sustainable development of the industry because it can help reduce resource consumption and identify environmental impacts and therefore improve production efficiency and environmental stewardship.

Life Cycle Assessment (LCA), which assesses the entire life cycle of product and provides quantitative and holistic analysis of resource use

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and environmental impacts, has wide applications in various organizations and industries as a popular tool for environmental impacts analysis. LCA has long been used to effectively analyze and evaluate the environmental impacts of traditional food products such as soybean, corn, wheat, and dairy products [10–13] while there are only a few studies on algae food or feed. Taelman et al. found that in terms of resource use, microalgae production for aquaculture purposes is more sustainable than the traditional fish feed in the scaled up scenarios [14]. More recently, same researchers compared the environmental sustainability of protein-rich algal meal and that of soybean meal for livestock feed applications [15]. A life cycle comparative analysis between *Dunaliella salina* microalgae and *Daucus carota* carrots for extracting beta-carotene as food additives revealed that the cultivation and harvesting of *D. salina* exhibited greater environmental impacts [16].

Those existing studies, however, were either on *Spirulina* as animal and aquaculture feeds [14] or on other algae species such as *Dunaliella salina*, *Scenedesmus*, *Chlorella* and *Tetraselmis suecica* [15–17]. There is no study conducted for algae as a supplementary food for human. Furthermore, current research results mainly came from small-scale outdoor cultivation with limited time and without involving all the processes that occur in an industrial setting. Therefore, there is a knowledge gap in life cycle environmental impacts analysis of *Spirulina* as a functional food for human in a large-scale production.

In this study, we quantitatively examined the life cycle (cradle-to-gate) of *Spirulina* production as edible functional food and conducted a comparative analysis with three other traditional foods or diets such as maize grain, milk and tofu. In order to evaluate the environmental and nutritional impacts of *Spirulina* products, several nutrient values (e.g., protein content and a composite nutrient score) were selected as functional units for analysis within LCA. Especially, the composite nutrient score was first applied as a functional unit for the algae LCA study. Another uniqueness of this study is the data used in our LCA analysis were mostly based on the actual data collected from a real *Spirulina* production plant. Therefore, our analysis would be accurate than those using data from the literature. In addition, the analysis was focused on algae nutrient production in China which is a region that had never been included in existing algae LCA studies. The results would generate significant interest in both LCA and algae research areas. Broadly, the project will help to promote application of algae as a food and nutrient source and thus increase diverse nutrients sources for human consumption. Lastly, as the LCA studies on all kinds of nutrients and food supplements are very rare in existing literature, this study were expected to fill the data gap and guide future studies in this area.

2. Methodology

2.1. Goal and scope definition

The LCA was performed according to the ISO standards (ISO 14040, 2006). The main goal of this study was to evaluate algae food production in terms of environmental performance on a life cycle base. The study was also aimed to identify the hotspots that raised the negative environmental impacts and the opportunities for improvement. In this study, the production of the edible *Spirulina* tablets, a commercial functional food, was modeled in an industrial scale. In addition, to explore the nutritional impacts of algae food, some high-protein edible food (e.g. maize grain, tofu and milk) were compared with algae tablets with various functional units (FUs). The results were expected to fill the data gaps in algal food industries.

All information on the cultivation system, harvest, and tablet manufacturing was obtained from an actual plant located in the city of Beihai in the south of China, N21°30′45.47″ E109°13′12.17″ (Fig. 1). The climate there, characterized by high temperature and abundant sunshine throughout the year (2009 h a year), is suitable for *Spirulina platensis* cultivation in the open pond system. During 2015–2016, this plant achieved a monthly production of 20 tons of *Spirulina* products in the forms of a powder tablet as dietary supplement for food or feed. The figures of algae cultivation and tablet manufacturing processes are shown in Fig. 1.

The system boundary for analysis is illustrated by the flow chart in Fig. 2. Cradle-to-gate environmental impacts of eligible *Spirulina* tablets were considered. The life cycle of algal tablets production was broken down into three discrete stages, namely inoculation and cultivation, harvest and dewatering, and tablet manufacturing which are described in the following section.

This study is for audience from the research community, the algae and *Spirulina* production industries and mass consumers of algae food. *Spirulina*, as the most successfully commercialized microalgae, may attract algae researchers for its large-scale production data and environmental impacts. The study outcome can also help edible *Spirulina* producers improve environmental performance by identifying key stage in their production processes, which will allow them to target energy and emissions reductions. In addition, the results may be useful for consumers because of the nutritional values and the safety issues of edible *Spirulina* products, which are still being questioned today in China. This study may give them answers through exploring a case study of whole *Spirulina* cultivation and tablet manufacturing processes.

2.2. Edible spirulina production in south China

2.2.1. Algae cultivation (preparation and cultivation)

Our algae production started with inoculant enrichment, which was accomplished indoor with a small photobioreactor (5 L). Microalgae cultivation, which requires large amount of nutrients (nitrogen and phosphorus), salts, CO_2, light and water, has significant environmental impacts and intensive energy consumption of the whole life cycle [18]. The culture medium was prepared in the medium tank, where different nutrients and salts were mixed and then pumped to each open pond. Sodium bicarbonate was mixed and added every few days as the main inorganic carbon source. The paddlewheel worked about 10 h per day for the suspension of microalgae. The freshwater was pumped from underground and reused after harvest and thus the water consumption was mainly due to evaporation. During cultivation and pre-harvest stage, food grade CO_2 was pumped into medium from CO_2 bottle for the pH regulation of the medium.

2.2.2. Algae powder production (concentration, drying and sieving)

The harvest system, with a series of dewatering and drying steps, is designed to progressively concentrate the algae biomass. The dewatering process, which involves a few stages of filtration, together with the following drying process is energy intensive. At first, fresh water was pumped to wash the algae cells, in order to eliminate their excess of salts and with the required degree of water content. Then, an industrial spray dryer was used for rapid drying. The extremely short drying time minimized the exposure of algal biomass to heat and oxygen which can cause undesirable changes to algal biomass. The loss of water contained in algae liquid during drying process is ignored in this study. Finally, the resultant algae powder with the concentrations of 95% solid content is directly used for tablets production [19]. In order to reduce the greenhouse gas impact, a biomass boiler was used to supply heat and the biofuels are wastes from agriculture such as wood pellet. Water collected in the harvest and dewatering containing many mediums, therefore it was recycled back to open ponds in order to reduce mediums and water use in the algae cultivation stage.

2.2.3. Tablet manufacturing

The harvested dry *Spirulina* powder (5% moisture) was transported to the tablet manufacturing workshop. With a series of tablet manufacturing processes, *Spirulina* tablets were produced as functional food which contains of 80% algae powder. The nutrient parameters of algae tablets are shown in Table 1 (supported by the test report of *Spirulina* tablets and USDA Food Composition Databases).

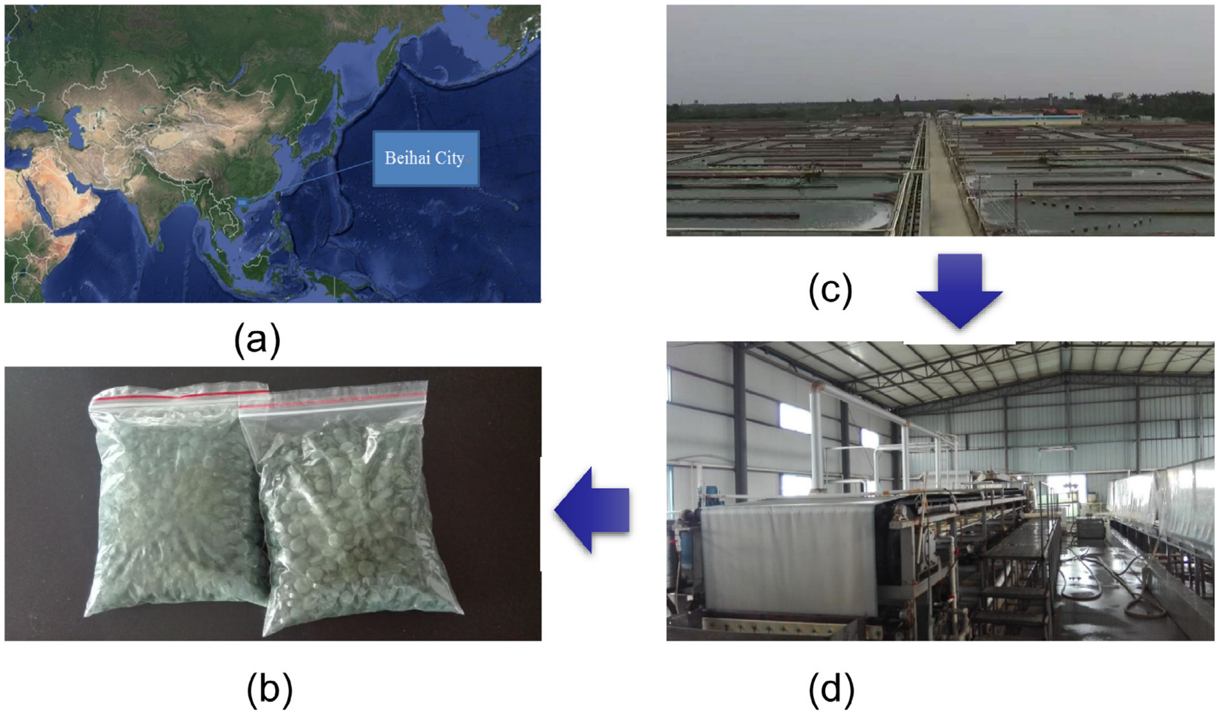

Fig. 1. The algae cultivation and tablet manufacturing plant. (a) Geographical location of Beihai city in the south of China; (b) the final algae tablets; (c) the open pond raceway cultivation system; (d) the algae dewatering and processing workshop.

2.2.4. Pollutant emissions

The residual diluted algal culture broth and tank cleaning wastewater were discharged into fishpond as fish cultivation nutrients. A small amount of algal residual paste produced during the harvest stage was processed to animal feed.

2.3. Functional units in LCA

The selection of the functional unit is extremely important in LCAs. Many LCAs of food products use mass or volume of the final products as functional units (FUs). Although these FUs appear to facilitate comparison between products, they fail to account for substantial differences in how various food products are actually used by consumers and what types of benefits consumers derive from these foods especially the nutritional values [20]. This study first used the mass based FU, i.e., one kilogram (kg) of algae tablets product to analyze environmental impacts. And then, other functional units including the protein content and a composite nutrient score (WNDS) were used in the study, in order to provide a comprehensive analysis and a fair comparison of the algae food with other foods.

The composite nutrient score used in this analysis was drawn from the study by Arsenault et al. It is a novel nutrient profiling algorithm that incorporates weighing of nutrients based on overall dietary quality in Healthy Eating Index (HEI) scores [21]. The WNDS includes eight nutrient characteristics which explained 65% of the variance in HEI scores. Five of these characteristics, including protein, fiber, calcium, unsaturated fat, and vitamin C, contribute positively to nutrition. Three characteristics which are: saturated fat, added sugar, and sodium all contributed in a negative way to nutrition. The regression analysis results in the following algorithm for determining a weighted nutrient density score (WNDS) [13, 21]:

$$\begin{aligned}\text{WNDS}=100 \times (&1.40 \times \text{Protein g per 100 kcal}/50\text{g}\\ &+ 3.13 \times \text{Fiber g per100kcal}/25\text{g}\\ &+ 1.00 \times \text{Calcium mg per } 100\frac{\text{kcal}}{1000}\text{mg} + 2.51\\ &\times \text{Unsaturatedfat g per 100 kcal}/44\text{ g} + 0.37\\ &\times \text{VitaminC mg per 100 kcal}/60\text{mg} - 2.95\\ &\times \text{Saturatedfat g per 100kcal}/20\text{ g} - 0.52\\ &\times \text{Addedsugar g per 100 kcal}/50\text{ g} - 1.34\\ &\times \text{Sodium mg per } 100\frac{\text{kcal}}{2400}\text{mg}\Big)\end{aligned} \tag{1}$$

These eight nutritional characteristics for the food products analyzed in this study are included in Table 2. Based on the calculation, the algae tablet has highest WNDS of all food for comparison in this study.

2.4. Life cycle inventory

In the cradle-to-gate analysis, we divided the algal tablets production processes into three production stages. The fundamental flows of each life cycle stages are listed in Table 3 in which the data were provided by the actual algal tablets production plant. Two scenarios were conducted in this study: an existing scenario (scenario 1) and an improved scenario (scenario 2). It is important to mention that scenario 1 is based on current operating and technical levels of algae tablets production, whereas scenario 2 is conducted with higher synthetic fertilizer and energy utilization efficiency depending on the N and P contained in Spirulina tablets, which would be feasible in next 5–10 years. The major differences between two scenarios were in the algae production stage in particular the material uses for algae growth. The study expected the nutrient use will be reduced by *% from the existing level.

The life cycle inventory included process direct inputs like water and emissions including CO_2 and nutrients. It also include upstream impacts of process inputs including chemical use in preparation of the culture medium, the electricity used in the different production stages,

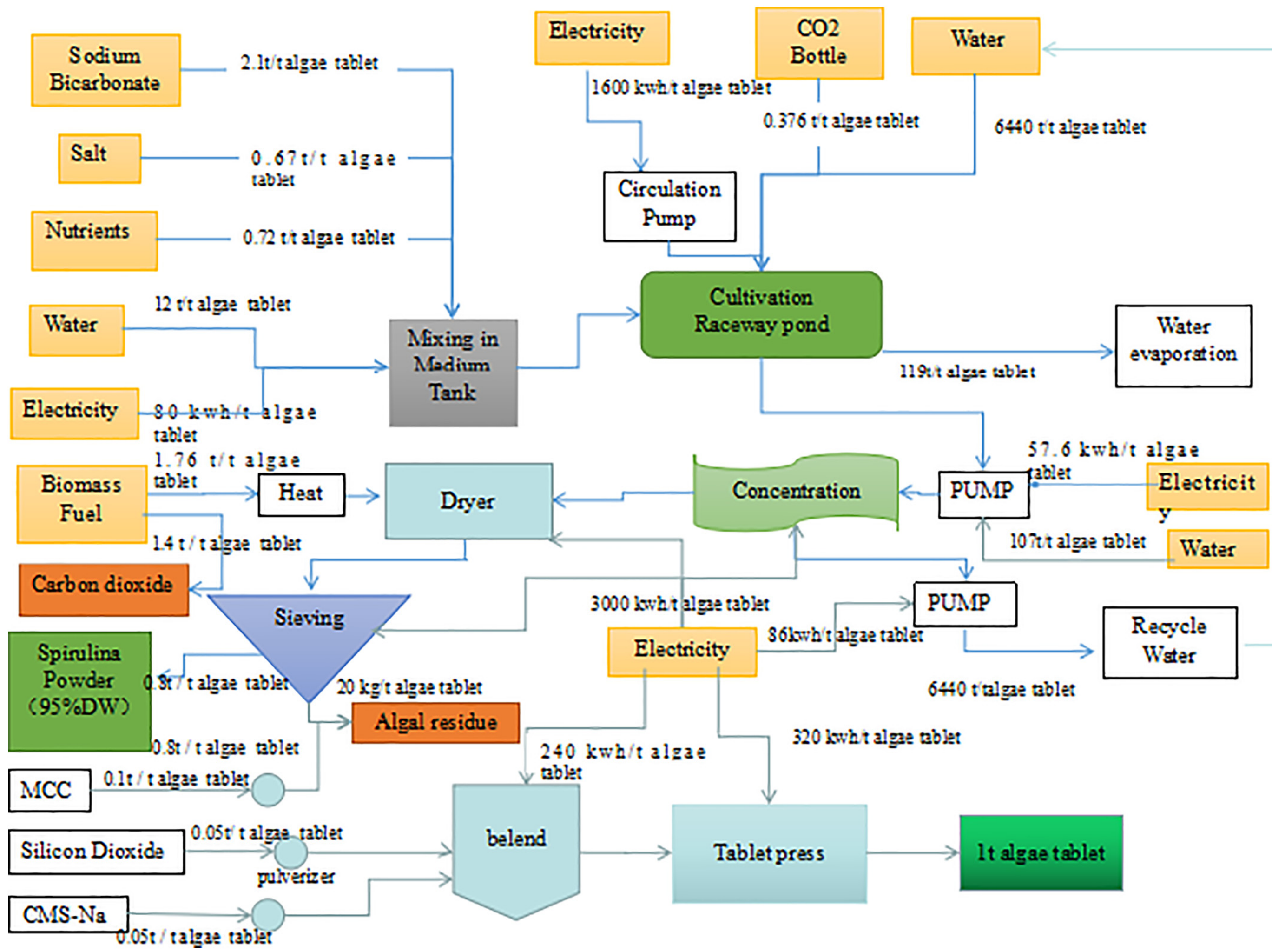

Fig. 2. System boundaries overview.

Table 1
The nutritional value of *spirulina* tablets.

Algae tablets	Per 100 g
Energy	1400 kJ
Protein	60.0 g
Lipid	3.5 g
Carbohydrate	10.5 g
Sodium	500 mg
Selenium	95.6 μg
Beta-carotene	40.0 mg
Vitamin C	8.5 mg

Table 2
Nutritional characteristics for the food products (USDA Food Composition Databases).

Characteristics	Units	Algae tablets	Maize grain	Milk (1% fat)	Tofu
g protein	Per 100 g	60	9	3.37	8
g fiber		3.6	8.4	0	0.4
mg calcium		120	5	119	162
g unsaturated fat		2.75	3.5	0.312	3.49
mg vitamin C		8.5	0	1	0.2
g saturated fat		2.7	1	0.633	0.65
g added sugar		0	0	0	0
mg sodium		500	5.9	44	8
kcal(food calorie)		336	366	42	77
g product	Per 100 kcal	30	27.3	130.9	129.9
WNDS	Per 100 g	191.09	135.75	11.94	53.61

the food grade CO_2 used in cultivation and pre-harvest stages, and some materials for the picking of algae tablets. Other impacts were not included into analysis. The upstream impacts of inputs production were based on Ecoinvent database, and are shown in Supporting Information (Table S1). Once the input was not a material established in Ecoinvent, a material with similar functions was used in LCI modeling, shown in the parenthesis in Table 3. The biofuels for heating was not counted as they all wastes from the farmlands in this study and assumed not be allocated with any environmental impact. The CO_2 emission from the biofuel heating system was not counted because it was a biological CO_2. The wastewater created in algae cultivation and harvest stage was not counted either as they all were discharged into fishpond as fish cultivation nutrients. The construction of tanks was not counted. The algae feed produced in the algae powder production stage were treated as a benefit for the production life cycle. The credits assigned reduced the impacts. The life cycle inventories of foods for comparison were also extracted from the Ecoinvent.

As the edible algae have not been analyzed with LCA, the study established a LCI for the algae production for biofuels in order to provide a base for comparison. In this scenario, the algae were supposed to grow in the open ponds with freshwater and synthetic fertilizers mainly Urea and DPA. The nutrients addition was modeled on the stoichiometric of algae, *Chlorella*, molecules. The flocculation and centrifuging processes were used for algae dewatering followed by the belt drying

Table 3
Inputs and outputs in the state of *spirulina* tablets production.

Processes	Unit	Scenario 1	Scenario 2
Cultivation			
Input			
Urea	T	0.632	0.19
Sodium nitrate	T	0.296	0.296
Sodium chloride	T	0.168	0.168
Potassium chloride	T	0.168	0.168
Sulfate	T	0.04	0.04
Phosphate	T	0.088	0.04
Sodium bicarbonate (ammonium bicarbonate)	T	2.1	1.34
Food grade CO_2 (CO_2 liquid)	T	0.376	0
Ground water (Tap water)	m^3	6452	6452
Electricity	kWh	2000	0
Outputs			
Water evaporation	m^3	119	119
Algae liquid	m^3	6333	6333
Harvest			
Inputs			
Algae liquid	m^3	6333	6333
Electricity	kWh	3200	3200
Ground water	m^3	107	107
Animal feed	T	1.76	1.76
Food grade packaging bag (can be ignored)	/	40	40
Outputs			
CO_2	T	1.408	0
Algal residue (used as feed)	kg	20	20
Algae powder	T	0.8	0.8
Recycled water	m^3	6440	6440
Tablet manufacturing			
Inputs			
Algae powder	T	0.8	0.8
Microcrystalline cellulose (Carboxymethyl cellulose)	T	0.1	0.1
Colloidal silicon dioxide (Can be ignored)	T	0.05	0.05
CMS-Na (maize starch)	T	0.05	0.05
Electricity	kWh	560	560
Bottle	/	10,000	10,000
Outputs			
Algae tablets	t	1	1

with natural gas as a fuel. The product from this system is dry algae powder with around 10–20% moisture. The LCI data were stemmed from the study by Mu et al. 2014 [24].

2.5. Impact analysis

The impact analysis followed the guidance in the ISO 14040, 2006. Only classification and characterization were conducted in this study. The normalization and weighting were not conducted because they are optional analysis required in the ISO standard and not necessary to realize the goals set for this study. The environmental results associated with the production of *Spirulina* tablets were characterized based on the TRACI 2 method for the Life Cycle Impact Assessment (LCIA) embedded in the Ecoinvent 2.2, 2010 database because it covers major impact categories including: ozone layer depletion potential (ODP), global warming potential over a 100-year timeframe (GWP), smog, acidification potential (AP), eutrophication potential (EP), carcinogenics, non carcinogenics, respiratory effects, ecotoxicity and fossil fuel depletion.

3. Results and discussion

3.1. Life cycle impacts of 1 kg algal tablets

The results of LCA (cradle-to-gate) of 1 kg algal tablets production at a commercial scale plant are presented in Table 4 for two scenarios. The impacts of the dry algae produced for biofuels are also listed for comparison. In general, the results showed the algae tablets production would cause environmental impacts of Global Warming (7.7 kg CO_2 eq.), Smog (0.44 kg O_3 eq.), Acidification (0.096 kg SO_2 eq.), Eutrophication (0.022 kg N eq.), and Fossil Fuel Depletion (12.7 MJ surplus). Impacts in other categories were minimal. Therefore, the major concerns of algae food production were still on the environment and ecosystems, instead of human health. A detailed analysis of each impact category was further conducted.

3.1.1. Ozone depletion

This is an impacts related to emissions of Chlorofluorocarbons (CFCs) and other halogenated ozone depleting substances (ODS) in the stratosphere. The ozone depletion potential of algae tablets production is 1.32 E–06 kg CFC eq. per kg tablets and the algae cultivation contributed to 67.2% of total ozone depletion impact. The direct emission of CFCs in algae tablet production was minimal. Impacts were mainly from upstream impacts of process inputs. Of all process inputs, the electricity use contributed 38% of total ozone depletion potential, followed by the sodium bicarbonate and Urea. Comparing to algae powder produced for biofuel production, the ozone depletion potential of the algae table production was more than 4 times. This was mainly caused by much higher electricity use in algae tablets production especially in algae drying and tablets making processes.

3.1.2. Global warming

This impact is related to emissions of greenhouse gases including CO_2, CH_4 and N_2O, and is measured by global warming potential, kg CO_2 eq. The LCA results showed the global warming potential for the algae tablet production was 7.7 kg CO_2 eq. per kg algae tablets, in which the algae cultivation stage contributed to 82% of total global warming potential. The global warming potential was mainly from indirect or upstream impacts of electricity and chemical production. The sodium bicarbonate and electricity use were two major inputs caused global warming potential and contributed to 35.4% and 21.4% respectively. The plant direct emissions were very low and mainly from emissions in the biofuel combustion process. Therefore, using biofuels to provide heat and electricity for plant's processes reduced the global warming potential. Comparing to algae production for biofuels, the producing algae for food had almost 3 times of GHG emissions of producing algae for biofuels. The higher electricity and nutrient uses contributed to this higher GHG emissions.

3.1.3. Smog formation

The smog formed in atmosphere from releases of pollutants and gases. It is measured by the mass of O_3 eq. released in the troposphere. The smog formation potential is 0.44 kg O_3 eq. per algae tablets produced. The algae cultivation contributed to 88.7% of total smog formation potential. The major input caused the smog formation potential was sodium bicarbonate in algae cultivation counting for 48.7% of total smog formation. There was no directly smog formation pollutant emission to the air from the plant. Comparing to the algae to biofuel production, the smog formation potential was 1.8 times. Again, the higher nutrient uses were the main reason for this higher impacts.

3.1.4. Acidification

This impact is related to acid substances released to air and usually leads to acid rain. Defined in the TRACI 2, the acidification is measured by the acidification potential with a unit of kg SO_2 eq. The acidification potential of algae tablets production was 0.09 kg SO_2 eq. in which 95% of the impact was from the algae cultivation. The urea used in this stage contributed to 69% of the total impact, because the acidification of urea production was much higher than other industries. The sodium bicarbonate caused 13.5% of the acidification potential and electricity used caused other 10%. There was no direct release into the ecosystem. The total acidification potential of algae tablets was 4 times of the algae

Table 4
Impact assessment results for the production of 1 kg algae tablets.

Impact category	Units	Scenario	Algae cultivation	Harvest	Tablets production	Total	% improvement	Algae for biofuels[a]
Ozone depletion	kg CFC-11 eq	1	8.87E–07	2.99E–07	1.34E–07	1.32E–06		2.72E–07
		2	4.41E–07	2.99E–07	1.34E–07	8.74E–07	33.79	
Global warming	kg CO_2 eq	1	6.32E + 00	7.82E–01	6.12E–01	7.71E + 00		2.8E + 00
		2	3.70E + 00	7.41E–01	6.12E–01	5.05E + 00	34.50	
Smog formation	kg O_3 eq	1	3.94E–01	1.89E–02	3.13E–02	4.44E–01		2.43E–01
		2	2.33E–01	1.89E–02	3.13E–02	2.83E–01	36.24	
Acidification	kg SO_2 eq	1	9.12E–02	1.36E–03	3.75E–03	9.63E–02		2.39E–02
		2	3.56E–02	1.36E–03	3.75E–03	4.07E–02	57.73	
Eutrophication	kg N eq	1	1.94E–02	1.49E–04	2.06E–03	2.16E–02		4.92E–03
		2	1.30E–02	1.49E–04	2.06E–03	1.52E–02	29.62	
Carcinogens	CTUh	1	2.59E–07	4.22E–08	2.85E–08	3.30E–07		1.29E–07
		2	1.54E–07	4.22E–08	2.85E–08	2.25E–07	31.85	
Non-carcinogens	CTUh	1	1.61E–06	−2.91E–07	1.69E–07	1.49E–06		5.18E–07
		2	9.65E–07	−2.91E–07	1.69E–07	8.43E–07	43.35	
Respiratory effects	kg PM2.5 eq	1	5.87E–03	8.06E–04	7.10E–04	7.39E–03		1.29E–03
		2	3.35E–03	8.06E–04	7.10E–04	4.87E–03	34.12	
Ecotoxicity	CTUe	1	5.67E + 01	8.48E + 00	4.76E + 00	6.99E + 01		1.78E + 01
		2	3.43E + 01	8.48E + 00	4.76E + 00	4.75E + 01	32.03	
Fossil fuel Depletion	MJ Surplus	1	9.76E + 00	2.03E + 00	8.94E-01	1.27E + 01		4.07E + 00
		2	4.96E + 00	2.03E + 00	8.94E-01	7.88E + 00	37.84	

[a] The results were based on the assumptions applied in the study by Mu et al., 2017 [24], in which the algae were assumed to produce in open ponds with freshwater.

produced for biofuels, in accordance with Scott Grierson, 2013 [23], reach in 0.0249 kg SO_2 eq.

3.1.5. Eutrophication

The eutrophication is caused by the nutrients, mainly N and P released into the aquatic system and is measured by kg N eq. released to the water. The study showed the eutrophication potential of algae tablets production was 0.022 kg N eq. per kg tablets, which was caused by every input in production. There was no input contributing significantly to eutrophication except the electricity use which caused around 14.5% of eutrophication. One important point need to be raised is the study did not count the directly N and P releases to the water in algae tablet production, because the wastewater was sent to the fish tank for beneficial reuse. The study assumed the nutrients were all taken by the fish and would not cause the nutrients release to natural water body. The eutrophication potential of algae tablets was 4.4 times to the algae produced for biofuels, because the nutrients use in algae cultivation were much higher than algae for biofuels.

3.1.6. Fossil fuel use

The fossil fuel use is an impact on natural resources and measured by the Surplus energy (MJ) need in future to extract fossil fuels. The study showed the fossil fuel use was 12.7 MJ per kg algae tablets produced, which was more than 3 times to the algae produced for biofuel (3.11 MJ). All the fossil fuel use was derived from indirect use of fossil fuel for nutrients and electricity. In particular, the fossil fuel consumption of sodium bicarbonate, urea and electricity counted for 33.3%, 19.0% and 28.1% of total fossil fuel use.

3.1.7. Ecotoxicity

This is a measure of toxic effects on the ecological system caused by natural or synthetic pollutants. The study showed the ecotoxicity of algae tablet production was 69.9 CTUe (acute toxicity) which was much higher than algae production for biofuels. The uses of sodium bicarbonate and urea were two major factors that caused higher ecotoxicity. As the toxic effects on ecosystems are related to the densities, concentrations, exposure, background/local conditions, and thresholds, it is difficult to assess if certain amount of CTUe could cause significant environmental impacts.

3.1.8. Carcinogenics, non-carcinogenics, and respiratory effects

These three impacts are related to human health. The carcinogenics and non-carcinogenics released from algae tablet production were around 2–3 times of algae production for biofuels. The production sodium bicarbonate was the major factor to the high impacts. The respiratory effects of algae tablets were much high than the algae production for biofuels. The major factor leading to PM 2.5 being released in algae tablet production was the sodium bicarbonate and the electricity uses. Similar as the ecotoxicity, these three impacts are related to many factors related to the source and the local conditions. If the releases of certain substances could cause significant human health impacts needs to be further examined and fall out the scope of this study.

The LCA study showed the algae cultivation is responsible for more than 60% of all impact categories under assessment especially in smog (88.7%), acidification (94.7%) and eutrophication potential (89.8%), which can be characterized as a key stage of environmental impacts in the algae tablets production chain. In contrast to the algae cultivation stage, the harvest stage with a series of dewatering and drying steps of this work caused much less impacts in the algal tablets production, ranging from only 1% to 20%. The electricity use was a major factor and contributed around 90% of impacts in this stage. The electricity was mainly used for algae harvest and dewatering. As the algae residue produced in the harvest stage was treated as a benefit which reduced the impacts of all categories. Even the impact of the non-carcinogens in this stage became negative. Lastly, the algae tablet manufacturing stage counted less than 10% of total impacts in various impact categories. The use of MCC and electricity were two major inputs contribute to impacts in this stage and contributed around 70% and 25% of impacts in this stage.

The study further analyzed the algae cultivation stage in order to figure out major factors that contribute to environmental impact in this stage. The contributions of each cultivation input to various impact categories are shown in Fig. 3. In the algae cultivation stage, the direct emissions were minimal. However, the preparation of the medium for algae growing plays a significant role in each impact category due to the high environmental footprints of the chemicals and nutrients. The medium counted for more than 80% of impacts in very impact categories in the cultivation stage. In addition, to ensure the high quality and quantity of algae products, excessive chemicals and nutrients were used in cultivation stage makes an insufficient utilization of resources and leading to much higher environmental impacts [17, 19]. Sodium

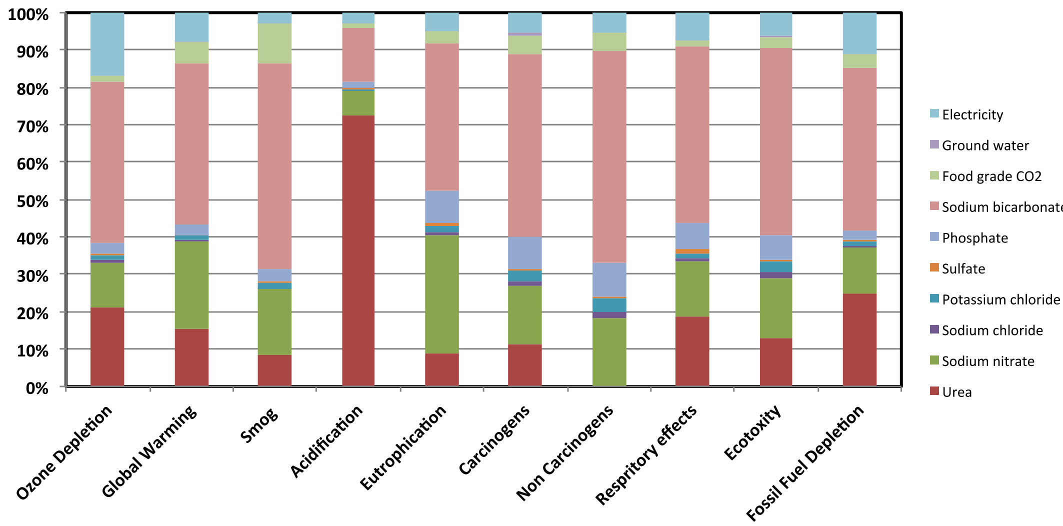

Fig. 3. Contributions of inputs to the impacts in the algae cultivation stage. The total impacts were set as 100%.

bicarbonate, for instance, the main inorganic carbonate source, contributed the most environmental impacts (40–50% of the total impact in this stage) in every category followed by the bicarbonate, urea, and sodium nitrate. The impacts caused by electricity use mainly for stirring paddle in this stage were less than impacts caused by nutrients and only contributed less than 10% of impacts in each category.

This result was not consistent to existing researches, such as the study by Scott Grierson, 2013 or Mu et al., 2014 [23,24], in which algae produced for biofuel production. In those studies the drying and dewatering stage contributed major impacts in algae production and electricity contributed as major upstream impacts. The impacts from nutrients production were counted less than 10% of total impacts in this stage. Consequently, the environmental impacts of algae production for biofuels are lower than those algae produced for nutrients supplements. For example, the GWP of algae for biofuel production was approximate 2.80 CO_2 eq. per kg dry algae (*Chlorella*) powder in an open pond system with Urea and DAP as nutrients. When producing algae for edible tablets, the impacts raised to 7.10 kg CO_2 eq. per kg dry algae powder produced. Although two studies used different algae species, but it showed the impact increased around 2.75 times per kg algae powder produced.

Therefore, the algae tablet producers should focus on improving the utilization efficiency of chemicals and nutrients and reducing the nonrenewable energy consumption in order to the decrease in the cost and environmental impacts of algae production. To decrease the environmental footprints of algae products, several strategies such as the following can be adopted: reactor design improvements, usage of renewable energy and mineral-rich water instead of fossil fuels and ground water, and recycling of waste CO_2 etc. A significant reduction in the environmental impacts on *Spirulina* product can be expected in the foreseeable future. Based on this, scenario 2 was conducted to explore the potential to reduce the environmental impacts of *Spirulina* tablets. As shown in Table 4, the environmental impacts of scenario 2 were different from scenario 1 only in the algae cultivation stage, because only the use of certain chemicals and nutrients were different. The overall impacts of scenario 2 decreases by 30%–40% compared to the existing scenario (scenario 1), mainly due to the increase of effective utilization of chemical fertilizers.

3.2. Comparison with other high-protein food

3.2.1. Comparison by per kg protein produced

The study compared the LCA results of algal tablets to other foods that could provide nutrients and energy to human or animal. First, the study compared the impacts of algal tablets with three high-protein foods, i.e. maize grain, milk and tofu in terms of protein production as the main function of algae tablets as protein source for human consumption. The relative importance of each impact category of the four foods is shown in Fig. 4 and the detailed results are shown in SI (Table S2).

Based on Fig. 4, the maize grain system shows much better environmental performances than the three other foods excluding the eutrophication potential. However, the corn grain used for comparison here was for animal feed. The actual impacts will be higher when the refining processes required for food grade production were accounted for. In contrast, the environmental footprints of milk (1% fat) are much higher than other food especially eutrophication potential. This is mostly due to the low protein content (3%) in milk and high environmental impacts of milk production.

Spirulina tablets have a much higher protein content than tofu (as much as 7 times) but their LCA results of two products per protein based were similar in 5 out of the 10 categories of the evaluated impacts such as global warming, smog, carcinogens, respiratory effects and fossil fuel depletion. This was because the life cycle impacts of tofu were not high in those categories as the results of the impacts per protein based were still low for tofu. The fertilizer use in soybean production has a great contribution to high eutrophication potential in tofu production. Whereas in the algal tablets production, recycling culture medium after the harvest stage reduced the consumption of nutrients and freshwater and hence resulted in the reduction in fossil resources depletion, environmental emissions and pollution caused by nitrate and phosphate and emission of ammonia and nitrogen oxide to the air from the fertilizers. The results of this study are consistent with that of the study by Hou et al. [25]. However, the algae tablets exhibit higher environmental impacts in ozone depletion and acidification due to the large amount usage of salts and nutrients (sodium bicarbonate, sodium nitrate and urea).

3.2.2. LCA results of per 1000 WNDS produced

Comparing algae tablets with other protein supplementary food or medicine is very difficult because the current LCA studies in the field of nutrient supplements are limited. So far, no study was found for the protein tablets or powder sold in nutrient stores. In addition, the nutrient components in the existing protein supplementary products might be different from the algae tablets. A fair comparison could not be made because different functions and nutrients were provided.

In this study, in order to evaluate the comprehensive nutritional value of each food, the weighted nutrient density score (WNDS) was

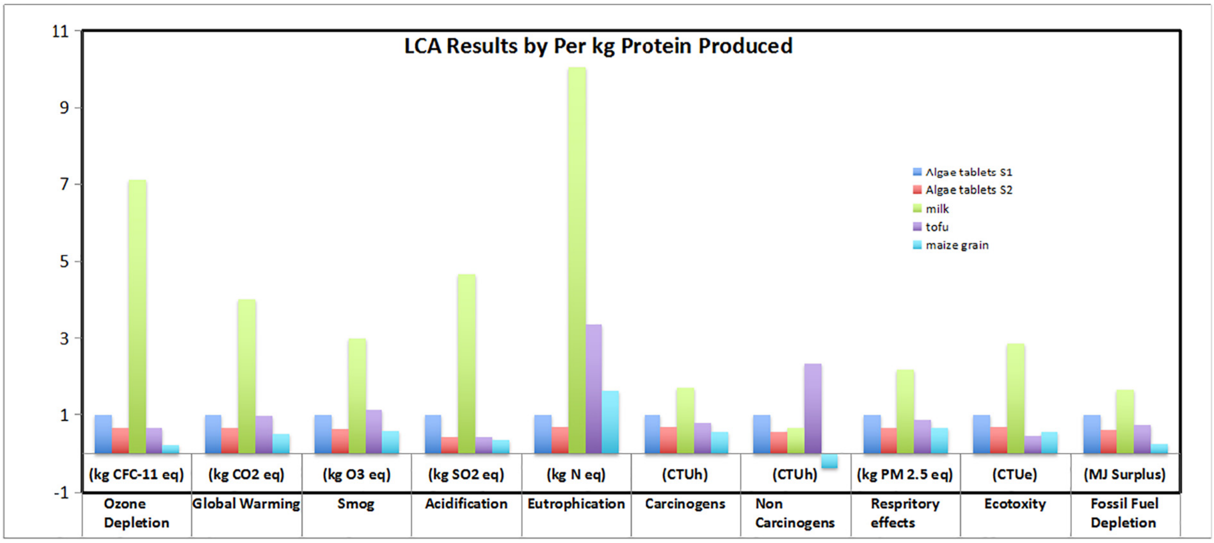

Fig. 4. Relative importance of protein foods to algae tablets by per kg protein produced. The impacts of algae tablets were set as 1.

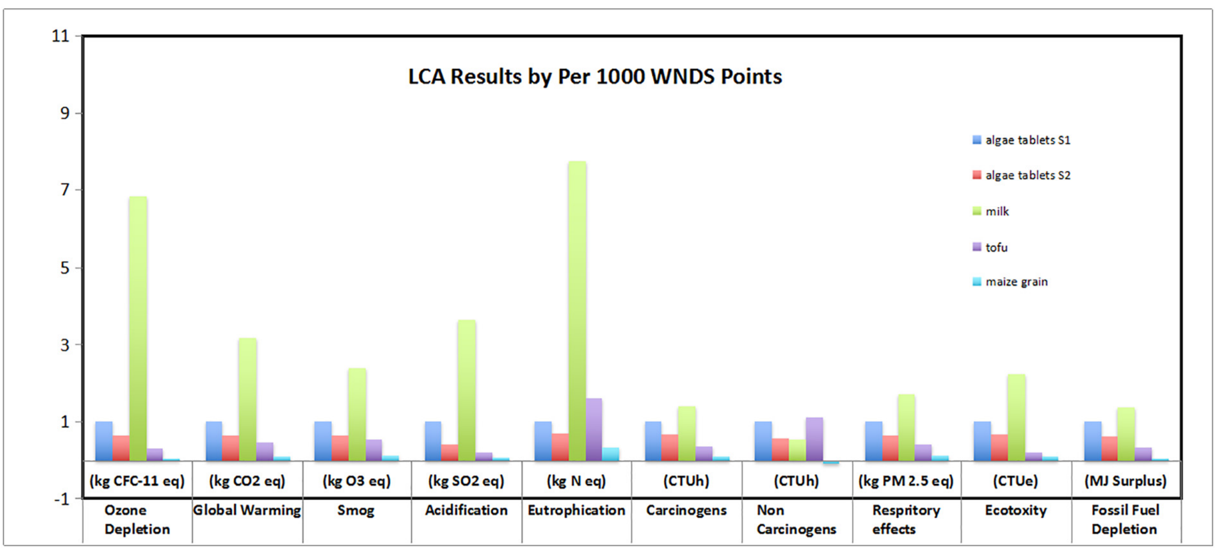

Fig. 5. Relative importance of impacts by per 1000 WNDS produced. The impacts of algal tablets were set as 1.

used as a functional unit in this study [21]. The LCA result of each food with the functional unit of 1000 WNDS points produced is presented in Fig. 5 and potential impact results for all the categories are shown in SI (Table S3).

According to Fig. 5, in terms of functional unit of per 1000 WNDS points, milk exhibited much higher environmental footprints than other food, and algae tablet is the second. The overall comparison results were same as the comparison on protein based. Obviously, the algae tablet is not competitive with plant-based nutrient food such as corn grains and tofu due to the high impacts in algae cultivation. However, it is better than animal based nutrient food such as milk. The large-scale cultivation and application of microalgae is still facing many challenges especially the huge energy demand and fertilizer overuse. In addition, β-carotene, bioactive compounds and minerals, which are widely contained in *Spirulina*, are not evaluated in WNDS. Thus, it is necessary to establish a more suitable functional unit for evaluating the nutritive value of algae food for human health completely.

3.3. LCA results between *Spirulina* tablets and high nutritive value food combination (carrot + tofu)

As shown above, *Spirulina platensis* is a suitable raw material for protein production due to its high protein and calcium content. Moreover, *Spirulina platensis* has up to 10 times more β-carotene than carrots per unit mass [26]. Thus, to evaluate the nutritive value and environmental impacts of *Spirulina* products fairly, a comparative life cycle analysis with high nutritive value food combination (carrot + tofu) that provides the same amount of protein and β-carotene is conducted. Based on the nutrient analysis of various foods, shown in Table 2, in order to provide same mass protein and β-carotene, it needs 7.5 kg tofu and 5.1 kg of carrot every 1 kg of algae tablets intake. The results are shown in Fig. 6 and the potential impact results are shown in SI (Table S4).

According to Fig. 6, *Spirulina* tablets exhibited lower environmental impacts than food combination (carrot + tofu). It means that *Spirulina* tablets are excellent alternative food for providing high-quality protein and β-carotene to a human being. However the large amount of salts and nutrients, especially urea used in algae cultivation stage, makes higher environmental impact of acidification. In addition, there are

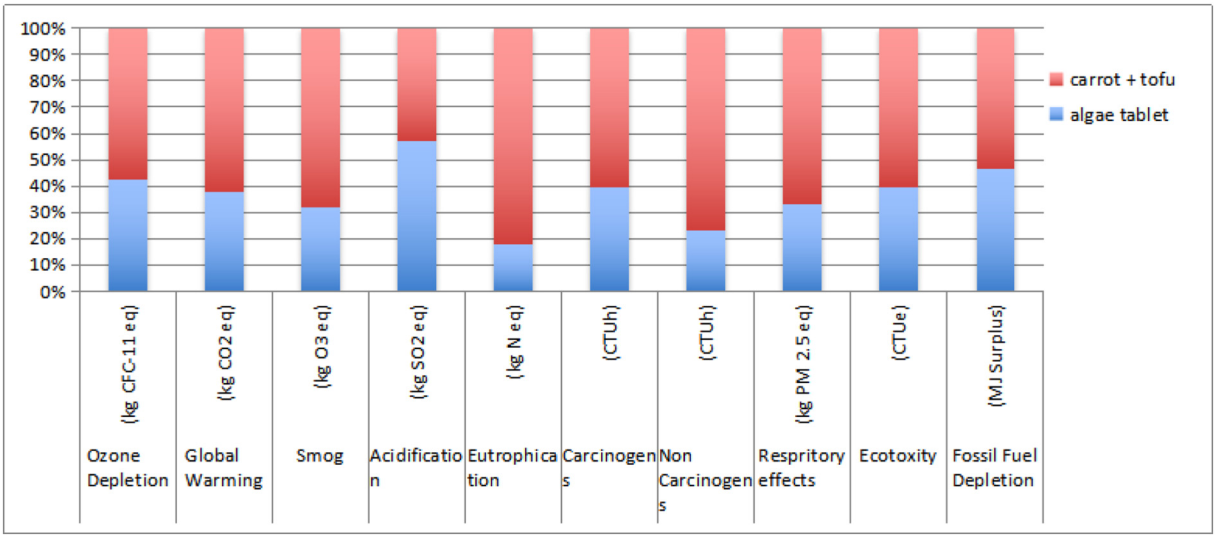

Fig. 6. Comparative life cycle analysis between *Spirulina* tablets and high nutritive value food combination (carrot + tofu).

some resource advantages in land, water and energy to produce microalgae rather than these traditional terrestrial crops. These advantages are as follows: more biomass produced per unit area due to a higher photosynthetic efficiency, no competition for space with food crops [27], reuse of the mediums, brackish and alkaline water can be used instead of fresh water and less energy consumption [28]. In general, *Spirulina* product has become one of the most promising and innovative sources of new food and functional products due to a high-level nutritive value [1].

4. Conclusions

Spirulina platensis is an ideal raw material for protein production in food and feed industries due to its high protein content (above 60%). The life cycle assessment of *Spirulina* tablets revealed that the edible algae production has 2–5 times high environmental impacts than algae produced for biofuels. This is due to the high nutrients use in the algae cultivation stage and electricity use for various processes. To decrease the cost and environmental impacts of algae product, several strategies such as reactor design improvements, use of renewable energy and recycle of CO_2 can be accepted. Unfortunately, *Spirulina* tablets are not competitive with traditional plant based nutritional food either in the WNDS based or the protein based functional unit. This is because many key functions provided by *Spirulina platensis* (e.g., beta-carotene, B vitamins, dietary minerals and GLA essential fatty acid) have been ignored in those functional units for comparison. Thus, it is necessary to establish a more suitable functional unit of algae food for evaluating the environmental and health impacts to a human being. In addition, the study conducted a deterministic analysis because the variances of process design and operation parameters were not available at this time. In the future, uncertainty analysis should be conducted in order to establish a reliable inventory in assessing edible algae food and products.

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Author's contribution

C.S. Ye, D. Mu, N. Horowitz, and Z.L. Xue developed the conception, designed the study and wrote the manuscript. C. Jie, M. X. Xue and Y. Zhou collected the data and performed the analysis. D.Y. Mu, W.G. Zhou and M. Klutts put forward for the design of the experiment, participating in the design analysis of the data and revising the manuscript. D.Y. Mu and W.G. Zhou participate in the design of the experiment, critically revising the manuscript and final approval of the version to be submitted.

Conflict of interest statement

There are no potential financial or other interests that could be perceived to influence the outcomes of the research.

Statement of informed consent

No conflicts, informed consent, human or animal rights applicable.

All authors confirmed that the manuscript authorship and agreed to submit it for peer review.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.algal.2018.07.013.

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